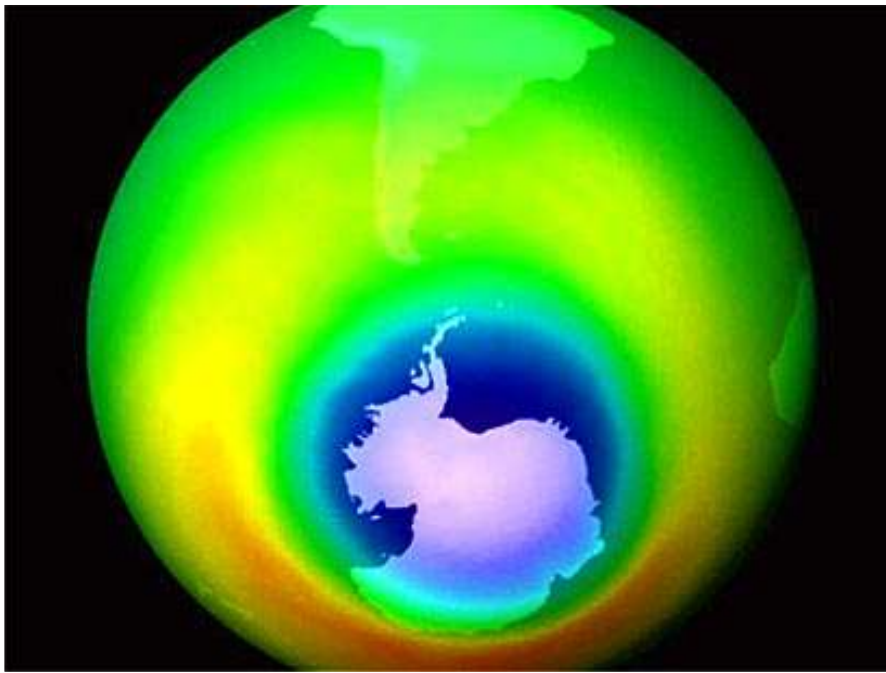


The Future of the Antarctic Ozone Hole

ANTA602: Critical Review



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Abstract

The detection of the ozone hole in the 1980s is considered one of the most important scientific discoveries of the past fifty years. Since then, it has been recognized as having a significant impact on the global atmospheric system, and in particular on Antarctic climate. It has recently been discovered that the Antarctic Polar Vortex, which forms during the polar winter as a result of ozone depletion, has played a major role in maintaining the stability of the East Antarctic Ice sheet over the last 50 years. Work is currently being undertaken to investigate the likely evolution of the Antarctic ozone hole in the future, in particular how a reduction in size might impact on Antarctic climate. It is possible that as the Antarctic Polar Vortex weakens the continent will no longer be shielded from the warming that has been occurring over the rest of the globe. As a result of this it is predicted that stratospheric temperatures could rise by up to 9° Celsius and that sea ice could decline by up to a third, if the size of the ozone hole is reduced to pre-1980 levels, as it is predicted to do by the end of the twenty-first century.

Table of Contents

| | |
|--|-----------|
| Abstract..... | 2 |
| Introduction | 4 |
| Causes of the Antarctic Ozone hole..... | 5 |
| Past changes in the Antarctic ozone hole..... | 6 |
| Predictions for the future of the Antarctic ozone hole..... | 7 |
| Impacts of future change on Antarctica and the Global System..... | 9 |
| Gaps in knowledge and directions for future research..... | 12 |
| Conclusion..... | 13 |
| References..... | 14 |

Introduction

The Antarctic ozone hole was first detected by the British Antarctic Survey's Total Ozone Mapping spectrometer in the early 1980s. Since then the importance of the ozone hole and the implications for global climate have been realized. This literature review covers the history, current state of knowledge and predicted future of the ozone hole, as well as the likely impacts that future changes will have on the Antarctic environment. Ozone depletion occurs when anthropogenically created chlorofluorocarbons (CFCs) released into the atmosphere react with ozone molecules, causing them to break down. This reaction occurs annually when the formation of the Antarctic Polar Vortex during the Antarctic winter separates the Antarctic stratosphere from other latitudes, causing extremely low stratospheric temperatures and subsequent formation of Polar stratospheric clouds. These provide a platform for the breakdown of ozone molecules, leading to the formation of the ozone hole when the photolabile molecules react with UV light as the sun returns in the Antarctic spring. Initially the ozone hole was not detected as the values recorded were so low that they were rejected by the recording satellite.

Since then it has been realised that the ozone hole has been present since at least 1980, which is now considered a baseline level for ozone amounts. Swift action was taken to limit the amount of CFCs released into the atmosphere. This came in the form of the Montreal Protocol for the protection of the environment. This has been extremely effective in reducing the amount of CFCs in the atmosphere, with a 95% reduction to date. It is thought that if these pollutants were removed from the stratosphere a recovery of the ozone hole over the Antarctic to pre 1980 levels is likely by the end of the twenty-first century. However, it is now becoming clear that the presence of the ozone hole over the Antarctic for the past 50 years has played a significant role in keeping the continent, and in particular the east Antarctic ice sheet stable, while the rest of the globe has shown a trend towards warming. Current research is now focused on delineating the future effects of the shrinking ozone hole on Antarctic climate.

Causes of the Antarctic ozone hole

The Antarctic ozone hole was first detected by the British Antarctic Survey's Total Ozone Mapping spectrometer (TOMS), which has been mapping ozone over the Antarctic since the late 1970s. Initial values recorded by the satellite for the entire Antarctic continent were so low they were disregarded as incorrect by the automated system. This meant that the full extent of the rapid decline in ozone was not discovered until the early 1980s, and published in *Nature* in 1985 (Jones, 2008). The very unusual atmospheric conditions over the Antarctic meant that standard numerical models for assessing impacts of halocarbons on the atmosphere were not able to predict the potential, and eventual massive stratospheric ozone destruction.

The 1985 British Antarctic survey paper published in *Nature* correctly identified that the decline in total ozone can be linked to an increase in chlorofluorocarbon (CFC) consumption, which in turn increases the amount of chlorine in the atmosphere (Farman et al., 1985).

The destruction of ozone occurs when chlorine and bromine emitted in the form of halocarbons at the earth's surface reach the stratosphere where they are involved in chemical reactions to form intermediate products. The majority of chlorine in the stratosphere is present in two forms, hydrogen chloride (HCl) and chloride nitrate (ClONO₂). These are referred to as reservoir gasses and they provide an effective means of distributing chlorine in an inorganic form throughout the stratosphere and into polar regions (Jones, 2008).

During the Antarctic winter extremely cold polar temperatures create an enormous temperature difference between the equator and the poles. This leads to the formation of a very strong westerly wind system, known as the Antarctic jet. This creates a vortex, the Antarctic Vortex, in which the air over Antarctica is effectively separated from that in the rest of the stratosphere. The very low temperatures within the polar vortex allow the formation of polar stratospheric clouds (PSCs). These provide a surface for reactions that convert halogen

reservoir gasses into molecules which are photolabile, or can easily be split apart by sunlight. These heterogeneous reactions occur on PSC surfaces throughout the polar winter, converting halogens into semi-active forms.

This means that when sunlight returns to the Antarctic stratosphere at the end of winter solar radiation rapidly splits the photolabile molecules releasing halogen atoms. These rapidly react with and destroy ozone, forming ClO and BrO. Due to the presence of the vortex the levels of these contaminants can increase to extremely high levels, creating an extremely destructive positive feedback cycle within the vortex. Through this process the ozone hole is formed within a matter of weeks at the beginning of the Antarctic spring. This cycle of depletion occurs until the end of spring when the atmosphere warms and the vortex breaks down, allowing stratospheric ozone concentrations to return to normal for the rest of the year. The cycle is repeated the following winter (Jones, 2008).

Past changes in the Antarctic ozone hole

Since its discovery in the 1980s the development of, and changes in the areal extent and depth of the Antarctic ozone hole have been closely monitored and observed with interest by the international scientific community. Conventionally it is considered that there is an ozone hole when ozone abundance is less than 220 Dobson units (DU) in a specific geographic place (Alvarez-Madrigal & Perez-Pereza, 2005).

It was originally suggested that the presence of the ozone hole could be explained on the basis of solar cycles or purely by atmospheric dynamics. It is now well known, however, that the main cause of reduction in Antarctic ozone can be attributed to anthropogenic activity (Alvarez-Madrigal & Perez-Pereza, 2005). In addition to this it can be shown that ozone abundance is also affected by natural phenomena such as the solar cycle of ultraviolet radiation, volcanic eruptions, temperature interannual changes, atmospheric dynamics, large solar proton events, galactic cosmic rays and the relativistic electron precipitation (Jackman et al., 1996 cit.)

The time scale over which ozone data is recorded and analysed is important in interpreting the history and the possible future of the ozone hole. It is clear that high-resolution data, such as that which is recorded daily does not produce a clear overview of long term patterns. Monthly averaged ozone hole size (OHS) data provides a more accurate overview for interpretation of long term trends.

Data from Alvarez-Madriral & Perez-Pereza (2005) shows an increase in OHS from 1982-2003, where data has been analysed on a monthly timescale. OHS is recorded and compared for the months of September, October and November. They also determine that OHS growth is most rapid in September, at the start of spring.

Changes in trends in six-year sub-sets of the OHS for the month of September show cyclic-like behavior in the past 22 years, which approximately follow solar flux index values (Alvarez-Madriral & Perez-Pereza, 2005). This would indicate a need to further investigate the relationships of underlying phenomena, to OHS.

Predictions for future of the Antarctic ozone hole

As the ozone hole was first identified in the 1980s, a 'full recovery' would be considered a return to pre-1980 ozone levels, of around 220 Dobson units. After the discovery of the depletion in the 1980s rapid steps were taken to reduce the size and impacts of the ozone hole. This began with the Vienna convention for the Protection of the Ozone layer signed by 20 states and the European community in 1985. This laid the legal framework for the Montreal Protocol on substances that deplete the ozone layer, which came into force in 1987. The Montreal protocol consists of regulations whose purpose is to control, reduce and eventually eliminate the production and use of the growing list of ozone depleting substances (ODS), with the aim of reducing halocarbon use and through that reducing the destruction of the Ozone layer. This agreement is considered one of the most successful examples of environmental cooperation to date. It is incredibly flexible and has been amended multiple times to reflect the changing conditions and updated science surrounding the problem. It has

successfully reduced global ozone-depleting chemical emissions by over 95% (Green, 2009) and it is widely accepted that a full recovery of the ozone hole is likely, but estimates of the timescale over which this is likely to occur are variable. However it is generally agreed that pre-1980 ozone levels are likely to be reached sometime in the late twenty-first century.

Research and subsequent prediction of the anticipated recovery period by Hofmann (1996) estimates that the total concentration of ozone depleting substances 'will peak in the stratosphere between 1997 and 1999 and the ozone hole would begin to heal slowly, reaching pre-ozone-hole levels by about the year 2050'. Hoffman also predicts that it is possible that the first signs of healing could be detected early in the twenty-first century, and more specifically that detection of the turnaround should be possible by the year 2008.

This is supported by more recent work published by Alvarez-Madrigal & Perez-Pereza (2005) who state that it is well known that 'effective equivalent stratospheric chlorine' (EEFC) peaked in 1997, and then decreased in 1998, up until the present. Consequently a reduction in the Antarctic ozone hole parameters of depth and areal extent is expected. They claim that the evolution of the OHS during the months of October and November shows signs of a reversal of the OHS trend that can be interpreted as the first steps of the process towards full ozone recovery. This is because it is thought that 'EEFC provides a rough estimate of the timescale for ozone recovery' (WMO, 2003 cit.), although no signals of the beginning of full ozone hole recovery can be seen yet.

More recently, work published by Newman et al., (2006) predicts that a full recovery to pre 1980 levels is to occur in approximately 2068. Their data is modeled to include a 6-year lag to account for the delay of ozone depleting substances to arrive over Antarctica. They estimate that recovery will occur in three phases:

- 1) Cessation of the growth of the ozone hole area
- 2) Turnaround when ozone begins to increase

3) Full recovery to 1980 levels, the date when the ozone hole has zero area

Newman et al., (2006) are of the opinion that the first phase of recovery is occurring presently, that the ozone hole is no longer growing. This is also supported by SCAR (2009) concluding that as a result of ODS in the stratosphere decreasing at a rate of approximately 1% per year; the size and depth of the ozone hole have stabilized but neither are yet reducing. UNEP (2007) also anticipate that the ozone layer should be back to its pre-1980 levels and condition by between 2050 and 2075

The most recent report by SCAR (2009) concludes that by the middle of the twenty-first century springtime concentrations of stratospheric ozone will have significantly recovered, but not to 1980 values. This is due to the additional factor of increasing greenhouse gas accumulation in the troposphere and the warming that this is likely to cause. The warming will concurrently cause further cooling in the stratosphere, where destruction of ozone is likely to continue.

Alvarez-Madrigal & Perez-Pereza (2005) are also of the opinion that OHS evolution observed during September indicates that the OHS maximum has not yet been reached. This is echoed by Hofmann (1996) who maintains that interannual variation of OHS indicates that a minimum Dobson unit value is expected by the year 2000.

Predicted impacts of future change on Antarctica

Research indicates that although average surface temperatures have been increasing globally, the interior of Antarctica has exhibited a unique cooling trend during the austral summer and fall (Perlwitz et al., 2008); this cooling is attributed to ozone depletion. Perlwitz et al (2008) predict that as stratospheric ozone levels return to near pre-1980 levels by the end of the twenty-first century, large scale atmospheric circulation patterns, currently shielding the Antarctic interior from warmer air masses from the north will begin to break down.

The SCAR (2009) report is a comprehensive summary of the impacts of the environmental effects of Antarctic climate change. The report states that although it is expected that ozone concentrations over the Antarctic will recover, if greenhouse gas concentrations increase at the present rate then temperatures across the continent will increase by several degrees and there will be about one third less sea ice.

The major variability in the atmospheric circulation of the high southern latitudes is the Southern Annular Mode or SAM. Over the last 50 years the SAM became more positive as pressure dropped around the coast of the Antarctic and increased at mid latitudes. It is known that the positive phase of the SAM is strengthened by the ozone hole. This has led to an increase in westerly winds over the southern ocean by 15-20% (SCAR, 2009). The positive phase of the SAM has also led to a deepening of the Amundsen Sea Low with consequent effects on temperature and sea ice extent in the coastal region of West Antarctica. This can be seen on the Eastern side of the Antarctic Peninsula where stronger westerly winds bring warm, maritime air masses across the peninsular to the low lying ice shelves on the eastern side. As a result of this temperatures have risen during the summer and autumn at a rate of 0.41°C per decade. Changes in the SAM have also caused ice shelf retreat due to increased fracturing via melt water infilling of pre-existing crevasses and the penetration of warm ocean water masses beneath ice shelves, as the positive phase of the SAM drives warm circumpolar deep water upwards. Ice shelf loss consequently causes the speeding up of glacier flow from inland. It is likely that these effects will continue to be seen in the future.

The deepening of the Amundsen Sea Low is concurrently contributing to an increase in sea ice extent in other areas of the continent. According to SCAR (2009) the average sea ice extent has increased by 1% per decade over the continent. The greatest increase is observed in the Ross Sea, where sea ice extent is growing by as much as 4.5% per decade.

The recovery of the ozone hole combined with a continued increase in greenhouse gas emissions as predicted is likely to see the continued strengthening of the positive phase of the SAM, but at a less rapid rate than the previous two decades. Therefore further increases of surface winds over the Southern Ocean are expected in the polar Summer and Autumn (SCAR, 2009).

It can be shown that as ozone levels recover, the lower stratosphere over the polar region will absorb more ultraviolet radiation from the sun, due to the reduction in strength of the polar vortex and the subsequent reduced presence of polar stratospheric clouds. Ozone recovery is predicted to cause a rise in lower stratospheric air temperatures by as much as 9°C. This will reduce the strong north-south temperature gradient that is currently driving the positive phase of the Southern Annular Mode (SCAR, 2009).

Ozone hole recovery would weaken the intense westerly circumpolar winds that currently surround the continent, preventing warmer air masses from crossing into the continent's interior. Therefore Antarctica will no longer be isolated from the warming patterns that are currently affecting the rest of the globe.

Although the data available is only from the relatively short, recent instrumental period, which is dwarfed by the climate history of the continent, it is clear that the anthropogenic impacts of the ozone hole and increased greenhouse gasses are significant, on any scale. The effects of the anticipated continued increase in greenhouse gasses at the current rate over the next century will be particularly influential due to the speed at which they occur. The removal of the cooling effect of the ozone hole as it decreases in size will only exacerbate the problem. It is currently still unclear how the large ice sheets of the Antarctic will respond, due to the variable, dynamic nature of interactions occurring within the system.

However it can be concluded that the recent rapid changes are cause for concern.

Gaps in knowledge & directions for further research

It can be seen from the state of current research and knowledge that there is considerably more work yet to be done in order to accurately make two important predictions:

If and when the Antarctic ozone hole is likely to undergo a full recovery; and what the long-term implications of such a recovery might be for the Antarctic system, and also possible effects on the wider global climatic system.

Estimation of ozone forcing for the twenty-first century is complicated by the short chemical lifetime of ozone compared to atmospheric transport timescales and by the sensitivity of the radiative forcing to the vertical distribution of ozone (IPCC, 2007).

An important factor for consideration, which is emerging in new research, is the possible role of nitrate aerosols. It is predicted that rapid increase in NO_x emissions could produce enough nitrate aerosol to offset the expected decline of other forcing, by 2100 (IPCC, 2007).

Bodeker (2010) also notes that the timing of the recovery is very uncertain because of considerable natural variability and feedbacks with climate change; and that the use of Global Circulation Models (GCMs) to project future Antarctic climate change is limited because there is considerable interaction between changes in stratospheric chemistry, in particular ozone depletion, and climate. GCM models for future climate in Antarctica use specific ozone fields to incorporate these interactions, but any feedbacks between stratospheric change and climate change are then lost. To overcome this atmospheric chemistry could be directly incorporated into GCMs so that climate induced changes in stratospheric temperatures are automatically included in predictions. Consequently the dynamic and interconnected nature of the atmospheric and climatic system makes it exceedingly difficult to model. It is very hard to determine exactly what factors influence and are responsible for changes at any given time. This proves a constant challenge for climate and atmospheric

scientists; however research methods are constantly evolving as more is learned. This is an intriguing and highly relevant field that will be extremely important in the next 100 years as the state of knowledge on the ozone hole continues to evolve.

Conclusion

Since the Antarctic ozone hole was first discovered in the 1980s it has been recognized as having a significant impact on the global atmospheric system, and in particular on Antarctic climate. It has recently been discovered that the Antarctic Polar Vortex, which forms during the polar winter, largely as a result of ozone depletion, has played a major role in maintaining the stability of the East Antarctic Ice sheet over the last 50 years. This is the same atmospheric phenomenon that is now known to be responsible for rapid warming on the west Antarctic Peninsula. Owing to the relatively recent nature of this discovery, work is currently being undertaken to determine how changes to the Antarctic ozone hole in the future, namely a significant reduction in size, might continue to affect Antarctic climate. It is thought that, as the Antarctic Polar Vortex weakens, the continent will no longer be shielded from the warming that has been occurring over the rest of the globe. It is predicted that stratospheric temperatures could rise by up to 9° Celsius and that sea ice could decline by up to a third; if the size of the ozone hole is reduced to pre-1980 levels, as it is predicted to do by the end of the twenty-first century.

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